UltraScale Computing

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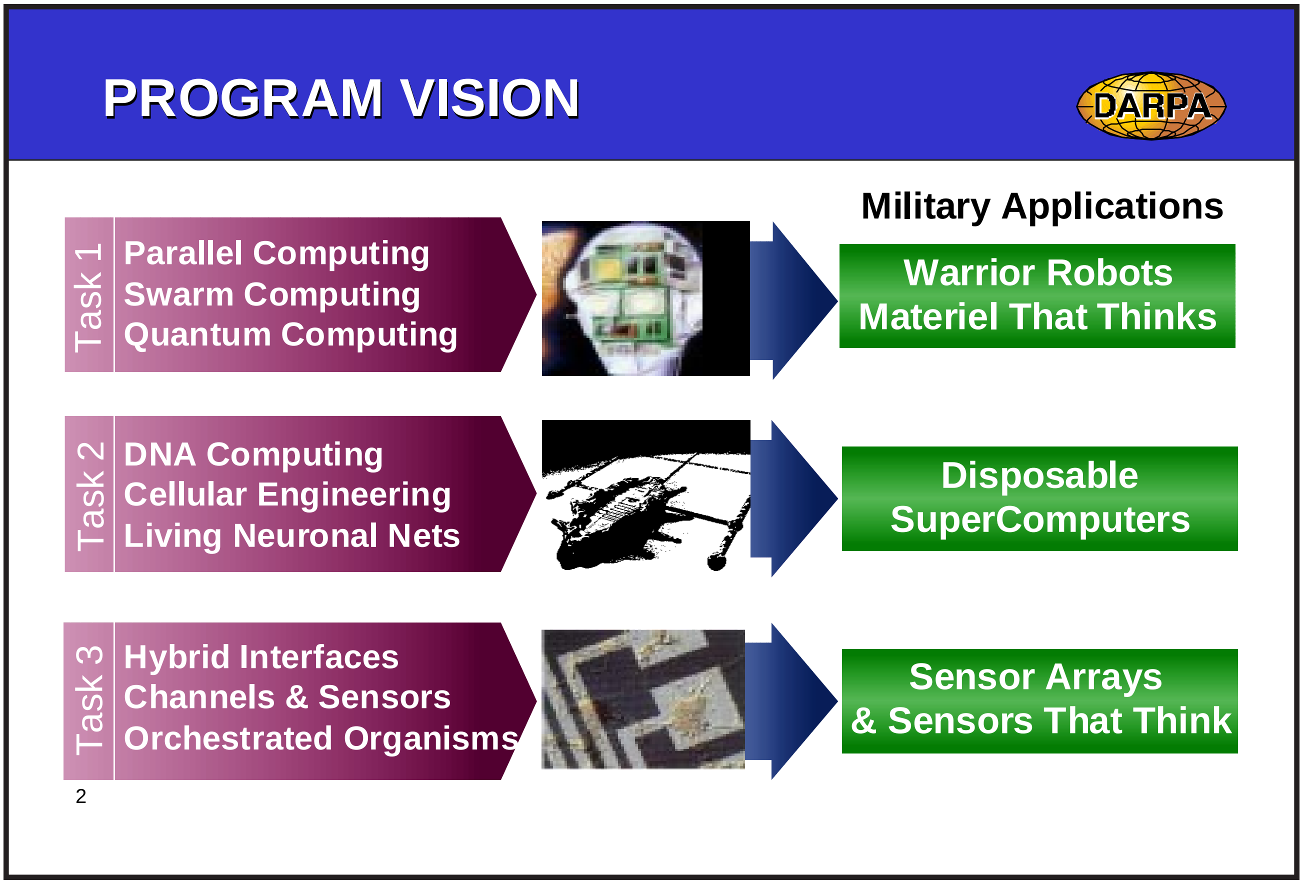
UltraScale Computing explores technologies that promise

- Ultra-large numbers of computational units.................................. > 10^{11} processors
- Ultra-small parts...................................... ~ interatomic distance dimensions
- Ultra-high performance........................... > Exaflops = 1,000’s of Petaflops
- Ultra-low power...................................... < 10^{19} ops/joule
- Ultra-complexity..................................... making “intractable” more tractable
- Ultra-smart.. machine inference & creativity



Having machines with human-like cleverness and humans with machine-like precision would revolutionize the battlefield.

- In warfare, as in computation, the best approach is the one that avoids the most hard work
- In computation, this is accomplished with algorithms; in warfare, this is accomplished with strategies
- The primary ingredient of both successful military strategies and computational algorithms is cleverness
- "A clever fighter is one who not only wins, but excels in winning with ease" – Sun Tsu

The limits of silicon digital technology will someday be reached. The technologies pursued on this program should at the least show promise of greatly exceeding the wildest extrapolations of current technology.

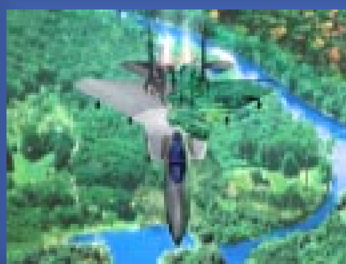
PROGRAM GOALS

DARPA

Machines with Human-Like Cleverness
Humans with Machine-Like Precision

Task 1- Models of Computation

Materiel That Thinks



Explore the upper reaches of computer complexity.

Task 2 - Physical Mechanisms

Disposable SuperComputers

Enable computing based on biological materials.

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Explore the upper reaches of computer complexity

New Models of Computation will develop new approaches to dealing with extremely large numbers of processing elements. At the millions of processor regime, languages, protocols and algorithms will be developed to interact with independent, unnamed and in some aspects unknown processors to elicit the "emergent behavior" we desire. At the upper end of complexity the use of superimposed and entangled quantum states of matter will be explored to examine the feasibility of "quantum computing" as a means of dealing with exponentially large problems currently beyond the scope of deterministic computers.

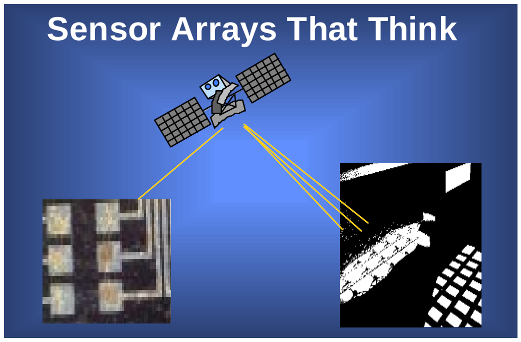
Enable computing based on biological materials

New Physical Mechanisms will explore the biological domain at three distinct levels: molecular level—the DNA molecule will be examined as a data storage and processing opportunity; one-celled organisms—these will be exploited as the bioengineers have done by manipulating gene structure to elicit desired behavior such as pattern replication, novel manufacturing and direct computing; and multicellular level—neuronal material will be cultured to produce patterned neural networks *in vitro* or (*in silico*) to directly interact with signals from electronic circuits.

PROGRAM GOALS (cont.)

Machines with Human-Like Cleverness
Humans with Machine-Like Precision

Task 3 - Hybrid Info Appliances



Interface biological materials with electronics to create hybrid appliances.

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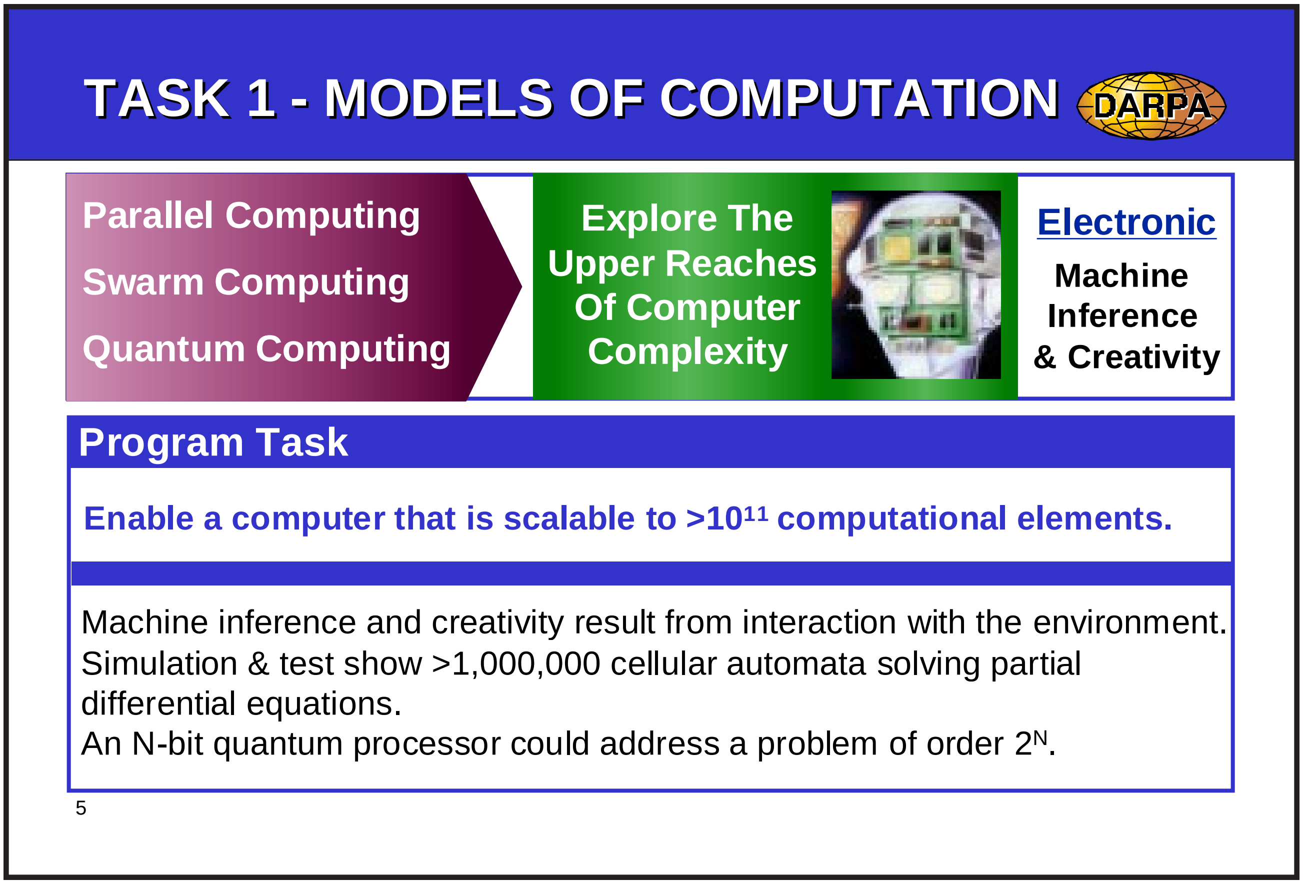
Interface biological materials with electronics to create hybrid information appliances

Hybrid Information Appliances will develop information processing, storage and communications subsystems that incorporate biological materials with electronic devices to achieve size, weight and power reductions of >100 over electronic-only equipment. Approaches to achieving this goal are (1) control growth of tailored organisms *in vitro* and *in vivo*; (2) bioengineer two-way communication channels which transduce electrical-optical-magnetic-chemical processes; and (3) orchestrate arrays of tailored organisms to perform computational tasks. Success could lead to technology for bio-enhanced electronics and electronically programmable biological processes.

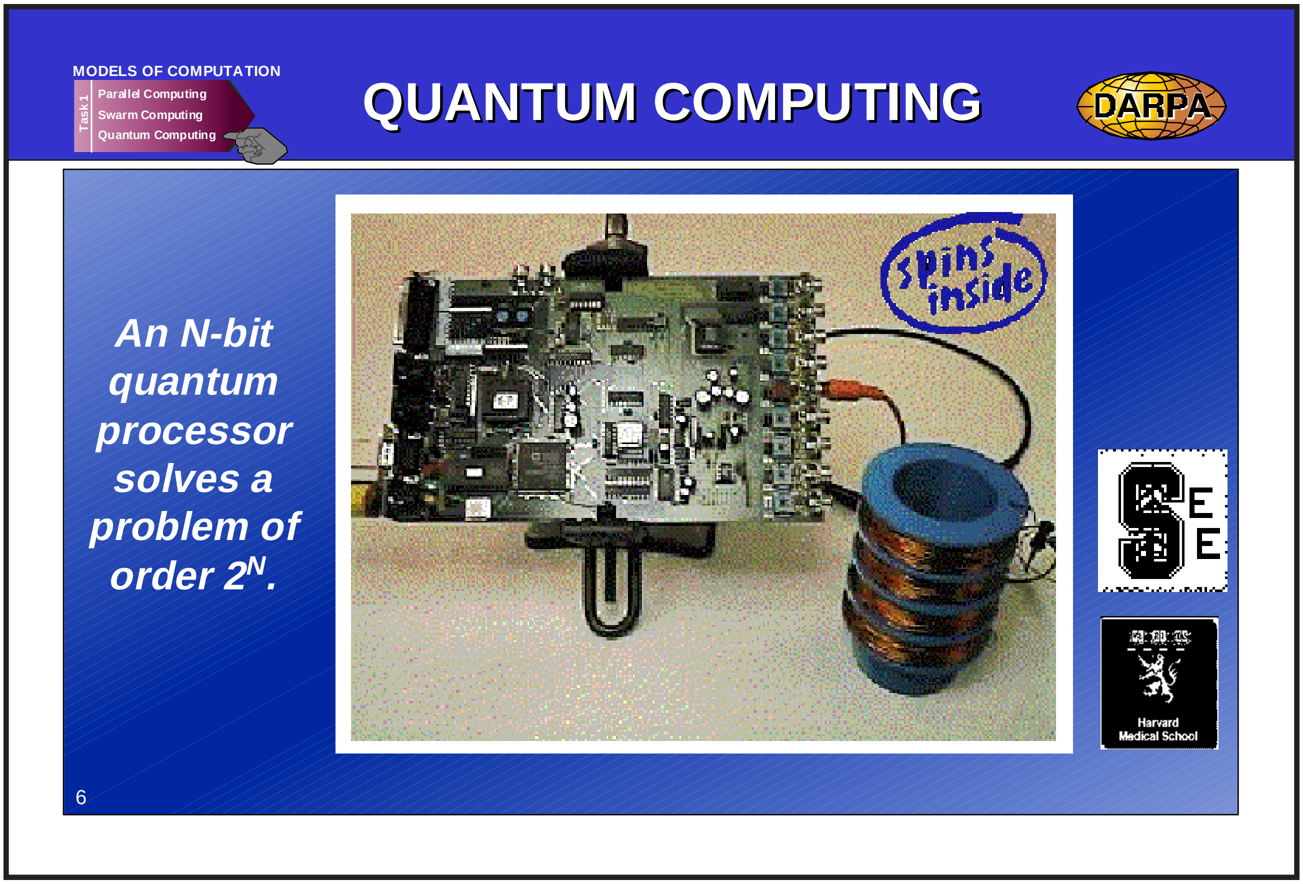
We will create interfaces that will vastly enhance the transfer of computer generated data and information in and out of biological systems. Approaches to achieving this goal are (1) establish direct broadband two-way interfaces to signals in nerve tissue; (2) transfer data to and from organic memory subsystems; and (3) create machine realizable symbolic constructs and persistent abstractions that support the representation and exchange of higher level constructs.



Can we get around the execution logic overhead of parallel computing and easily perform $>10^{15}$ logical operations per second and can we automate knowledge manipulation to the point where machines are clever enough to best opposing warriors?

- Here is where we explore the notion of utilizing ordinary transistors in extraordinary numbers—upwards of as many transistors as there are neurons in your head. Can we develop new models of computation that will greatly enhance what can be done with shrinking transistors and distributed shared memory?

  Here is also where we explore the use of quantum states of matter to store and process information. The superposition of quantum states—called quantum entanglement—provides a "free-space interconnect" amongst all participating nodes without delay or dissipation. It promises to redefine the class of problems that can be solved in polynomial time (P).



Ongoing efforts in quantum computing include

- The Quantum Information Center (QUIC) at CalTech is investigating cavity-confined photon interactions as a basis for quantum processing nodes; quantum protocols and algorithms for error detection and correction; and simulation of quantum programming.
- Two teams headed by Harvard Medical School and Stanford are investigating nuclear magnetic resonance as a domain for quantum or pseudo-quantum states that can be used to perform computations. This could provide an experimental alternative to trapping ions at 0.001 ^{o}K.

TASK 2 - PHYSICAL MECHANISMS

DARPA

DNA Computing

Cellular Engineering

Living Neuronal Networks

Enable Computation Based on Biological Material

Organic

Biology that Computes

Program Task

Enable computation based on biological materials.

Data stored & retrieved from DNA; a simulated problem is solved.

Finite state machines implemented via gene expression/transcription.

Two logic circuits grown in vitro & interfaced to underlying electronics.

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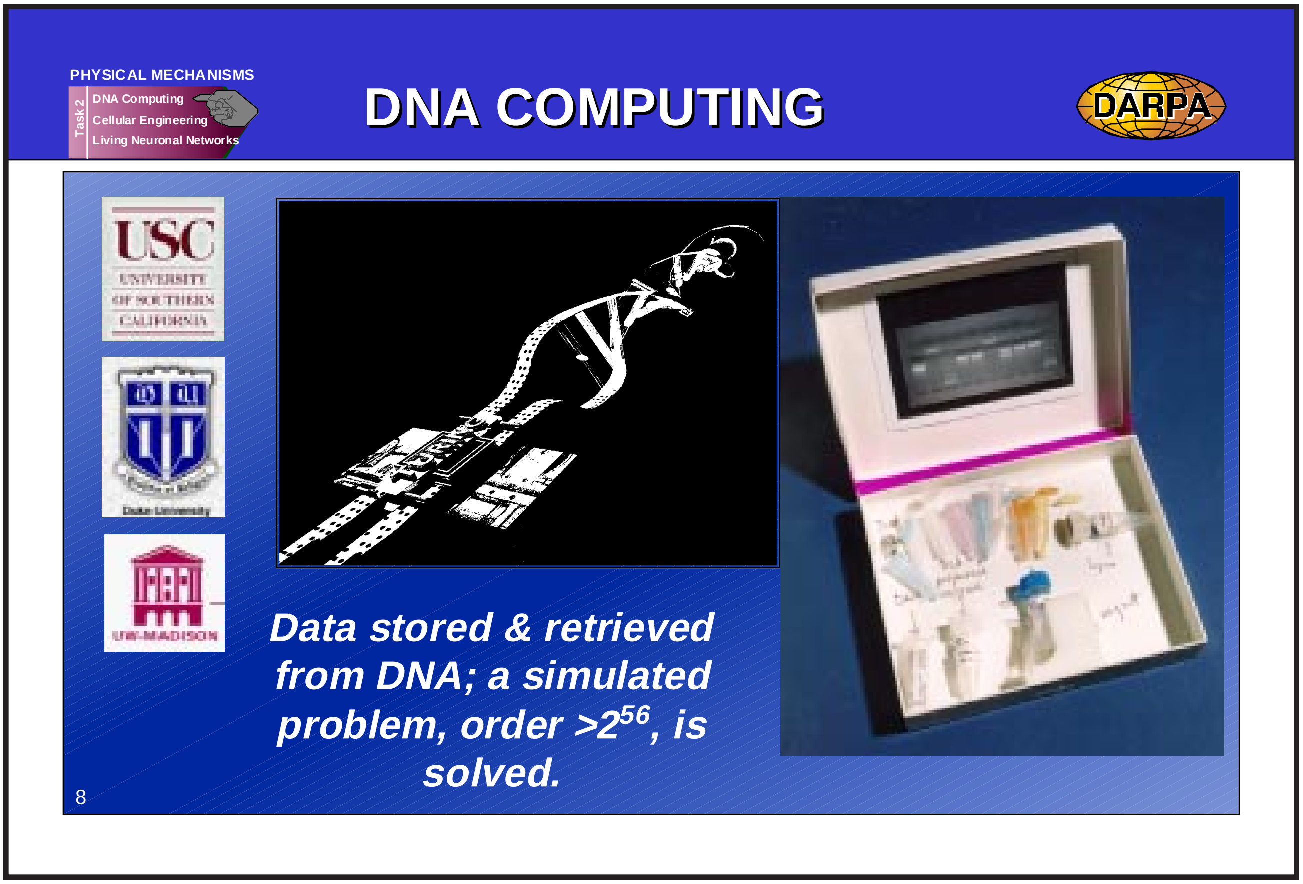
Explore biological artifacts that can be used to solve computationally difficult problems in an inexpensive, small, lightweight, low power manner.

Approaches to achieving this goal are

- Store and process data in DNA or other biological molecules
- Install input/output control mechanisms in one-celled organisms for direct computation or manufacturing of artifacts
- Culture biological two-cell neural circuits on a silicon circuit and exchange electrical signals between the biological and electronic media.



ITO-sponsored work on DNA computing includes

- University of Southern California and Princeton are developing theoretical and biological techniques for enzyme-free DNA computing to determine the limits of direct splicing (the sticker model) as a technique which may one day crack DES in less time than a supercomputer or Internet-based clusters.
- University of Wisconsin is developing surface-based techniques for biomolecular computing.
- Duke University is leading a team of multidisciplinary/multiuniversity researchers in biomolecular computing.

TASK 3 - HYBRID INFO APPLIANCES

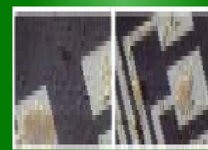
DARPA

Hybrid Interfaces

Channels & Sensors

Orchestrated Organisms

Interface Biological Processors With Silicon



Hybrid Information Appliances

Program Task

Interface biological materials with silicon-based computation.

Electronic control of the growth of tailored organisms *in vitro* & *in vivo.*

Two-way communication channels--electrical/optical/magnetic to chemical transduction.

Array of tailored organisms perform a computational task.

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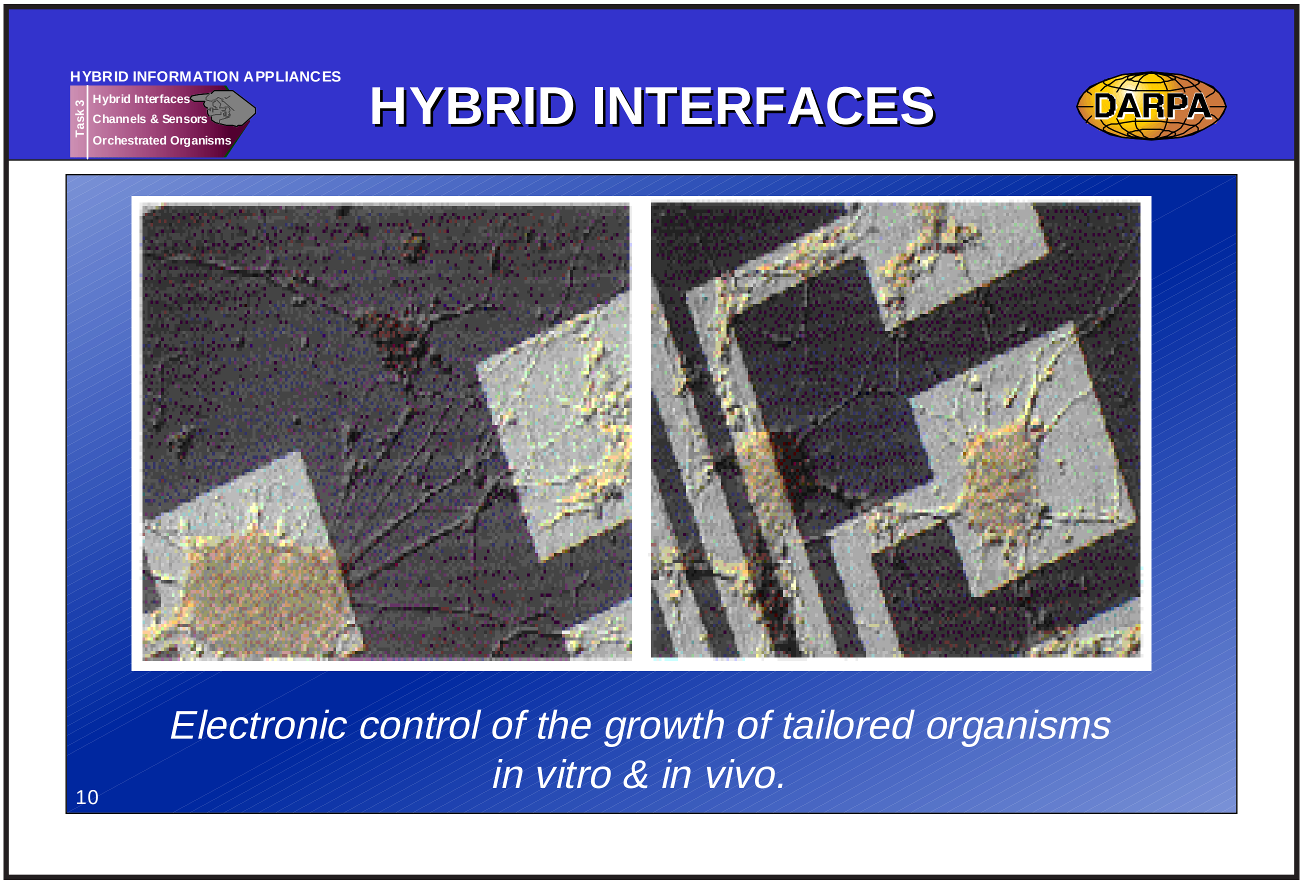
Hybrid Information Appliances will develop information processing, storage and communications subsystems that integrate biological materials with electronic devices to achieve size, weight and power reductions of >100 over electronic-only equipment.

Approaches to achieving this goal are

- Control growth of tailored organisms *in vitro* and *in vivo*
- Bioengineer two-way communication channels which transduce electrical-optical-magnetic signals to chemical processes
- Orchestrate arrays of tailored organisms to perform computational tasks

Success could lead to technology for bio-enhanced electronics and electronically programmable biological processes.



- Optical system stimulates neuron while recording neighboring neuron signals
- Maximize neuron lifetime by forming glial cell layers
- Robust microscopic electrical connections between neurons and solid state electronics

HYBRID INFORMATION APPLIANCES

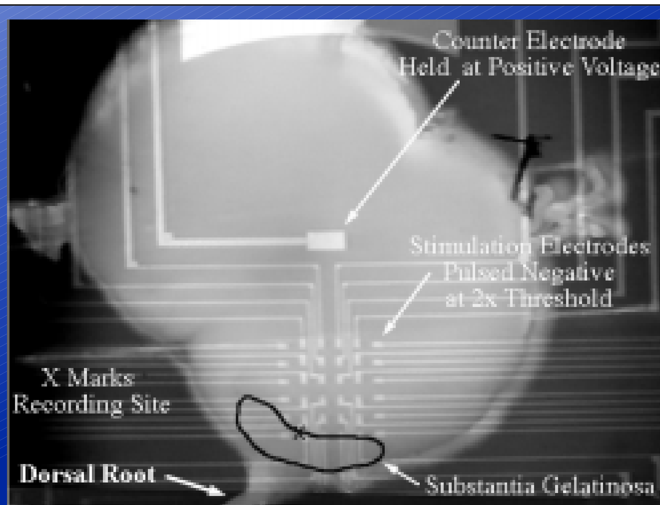
Task 3

Hybrid Interfaces

Channels & Sensors

Orchestrated Organisms

INTERFACE MECHANISMS



Two-way communication channels - electrical/optical/magnetic nerve tissue.

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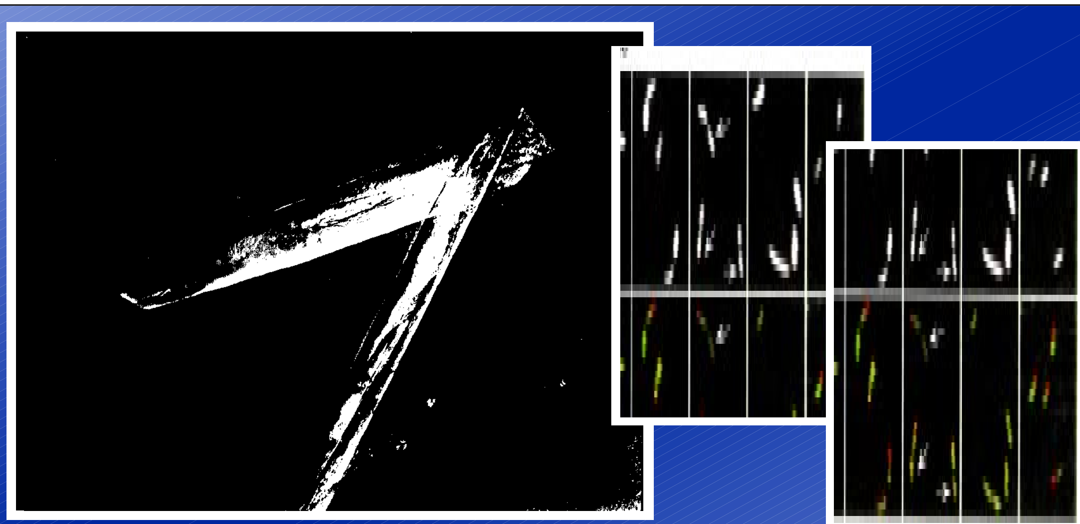
- Determine best interface model
- Map out responses of submicron nerve terminals to stimulation
- Evaluate electrical, chemical, magnetic and electromagnetic sensors for accuracy, precision, and facility
- Demonstrate signal processing methodology for transducing from tissue to electronics

HYBRID INFORMATION APPLIANCES

Task 3
Hybrid Interfaces
Channels & Sensors
Orchestrated Organisms

CHANNELS & SENSORS

DARPA



Bioengineer two-way communication channels which transduce electrical/optical/magnetic signals to chemical processes.

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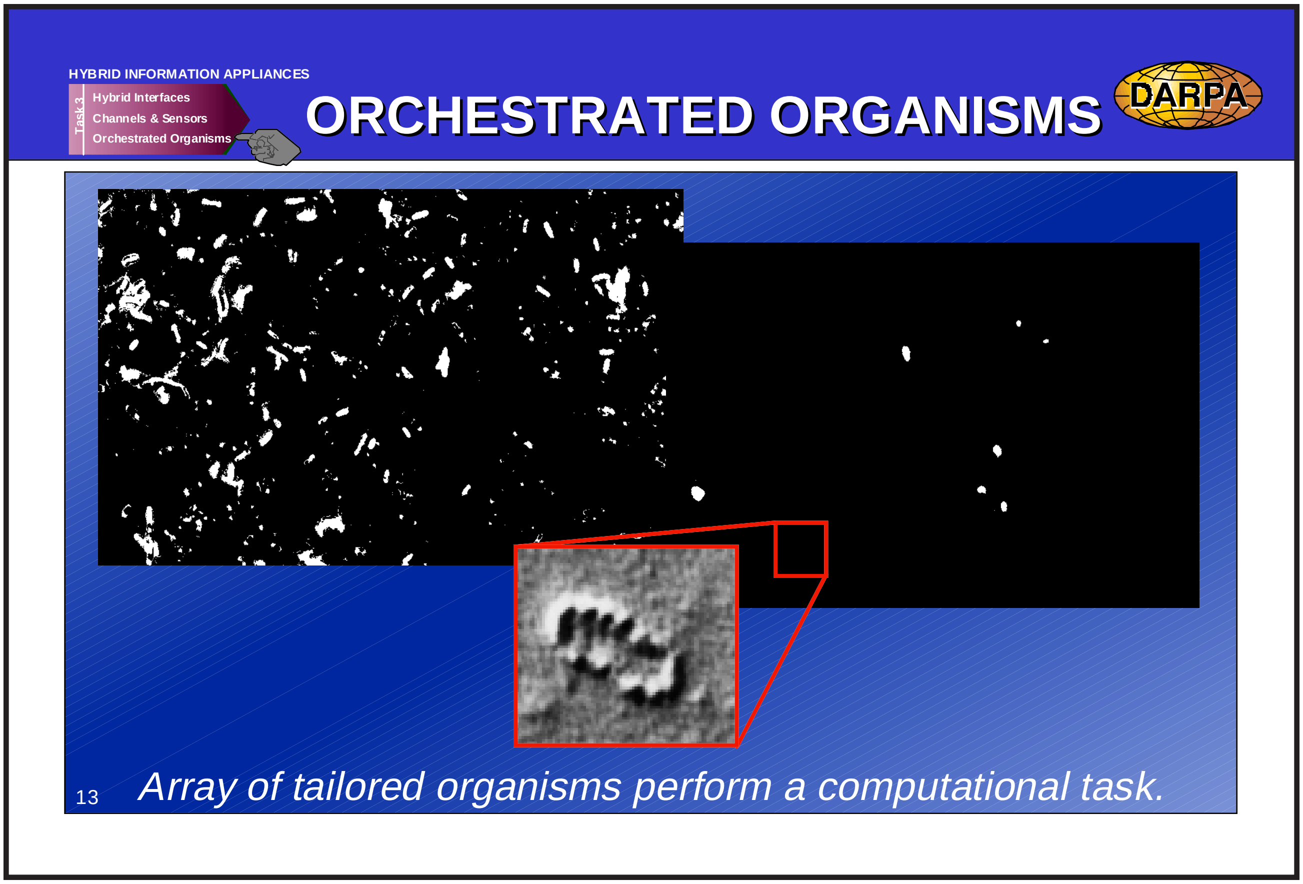
- Determine three-dimensional structure of the oscillator peptide using x-ray diffraction
- Demonstrate bioengineered two-way communication channels
- Investigate modification of peptide to engineer sensitivity to chemicals not normally found in the body



• Develop computational models of the controlling regulatory networks of cells

• Model and measure complete set of competing regulatory interactions in a cell

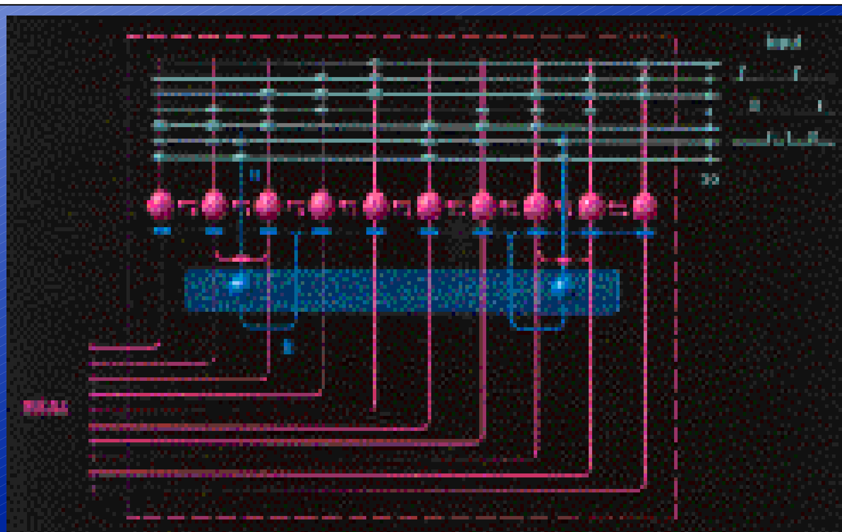
• Establish *in vivo* DNA-protein interaction codes for molecular switching of bacterial biomolecules and cells

HYBRID INFORMATION APPLIANCES

Task 3

- Hybrid Interfaces
- Channels & Sensors
- Orchestrated Organisms

MEMORY MODELS



Symbolic constructs and persistent abstractions for human thought.

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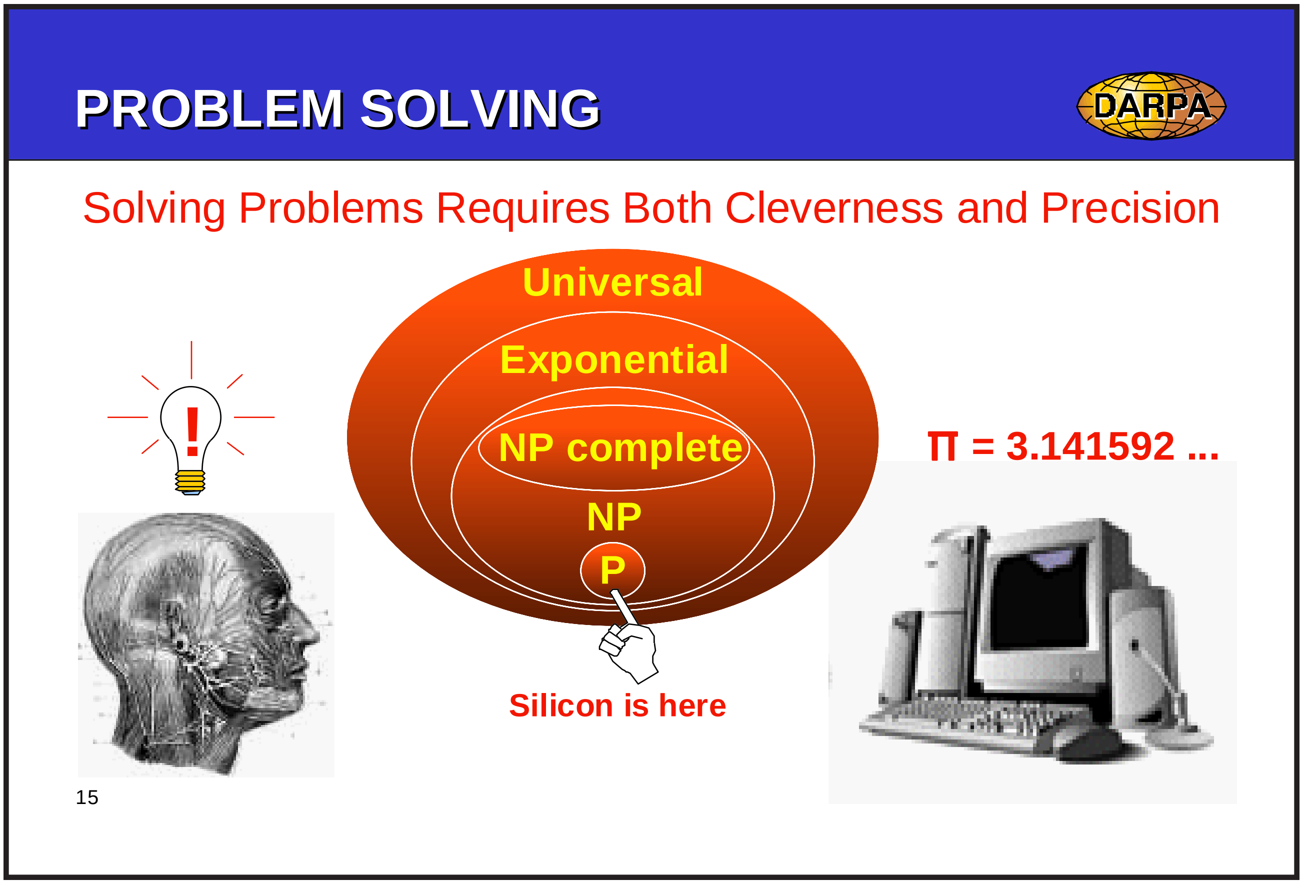
• Study network-level memory and behavior and synaptic and kinetic-level neural plasticity

• Evaluate memory models in simulation



• Humans invented information technology to help solve problems in the battlefield.

• The human brain is magnificent at reasoning and problem solving with **cleverness**

- Greek soldiers invented mechanical “computers” to optimize their catapults 300 years before the mathematicians invented the cube law representation which described the catapult’s behavior.

• Information technology is magnificent at recording and sorting data with **precision**

- The strength of information technology from papyrus to pentiums has always been the ability to store and manipulate inconveniently large quantities of data

• **Both cleverness and precision are of great value to the warfighter. This program tests the degree to which they can be enhanced and combined to solve problems in the battlefield.**